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THE TRANSVERSE MOTIONS OF THE SOURCES OF SOLAR RADIO BURSTS

J. P. WILD, K. V. SHERIDAN, AND G. H. TRENT
Radiophysics Laboratory, Commonwealth Scientific and Industrial Research Organization, Sydney, Australia

Observations of the spectrum of solar radio bursts at meter wavelengths have indicated the desirability of measuring positions on the sun's disk not only as a function of time but also as a function of frequency. With this objective in view, we are now using a swept-frequency interferometer to determine the east-west disk coordinate of the transient solar sources at time intervals of $\frac{1}{2}$ second and freqency intervals of about 5 Mc/s within the frequency range 40 to 70 Mc/s. The accuracy to which the centroid of the source is located is about ± 1 minute of arc. In its initial form [1], the interferometer contained two aerials separated by a distance of 1 km. As a result of preliminary tests, two major additions have been made: (1) a second interferometer of much smaller spacing ($\frac{1}{4}$ km) has been added to resolve the usual ambiguities associated with two-aerial interferometry, and (2) an automatic system of lobe-switching and phase-calibration has been incorporated to facilitate the reduction of the complex data recorded.

In its modified form, the equipment was put into operation on 1958 June 4, and the observations described here were taken during the ensuing 5 weeks.

1. TYPE III BURSTS

The first problem to be investigated concerns the physical interpretation of the short-lived bursts of spectral type III. These bursts, which often occur in groups near the beginning of solar flares, are characterized by a rapid drift across the spectrum of the frequency of maximum intensity: the sweep from 70 to 40 Mc/s, for instance, occurs in about 1 to 3 seconds. We wished to test by direct means the suggestion [2, 3] that the frequency drift is due to the excitation of plasma oscillations of frequencies that decrease with time as the exciting agency travels outward through regions of decreasing electron density in the solar corona. Assuming the usual estimates of electron density in the corona, the velocity of the exciting agency is calculated to be between 3×10^4 and 10^5 km/second.

The method was to search for transverse motions of the sources across the sun's disk: if the theory is correct the transverse velocity should often be comparable with the inferred radial velocities, especially in the case of disturbances near the limb.

Using the swept-frequency interferometer, the positions of a number of

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groups of type III bursts were determined as a function of time and frequency. In general the position of the source of a burst *at a single frequency* was found to change with time by amounts less than the experimental scatter* (less than ½ minute of arc for strong signals). However, different frequencies were found to arrive from different directions, often being dispersed across an appreciable fraction of the sun's disk. The variation is most marked for sources beyond the limb, where the lower frequencies appear to arrive from much greater heights in the corona than the higher frequencies, as much as 10 minutes of arc separating the 45 and 65 Mc/s positions. The results are illustrated in Figs. 1 and 2. Fig. 1 shows the positions of two type III groups, which appear on the same record within half an hour of one

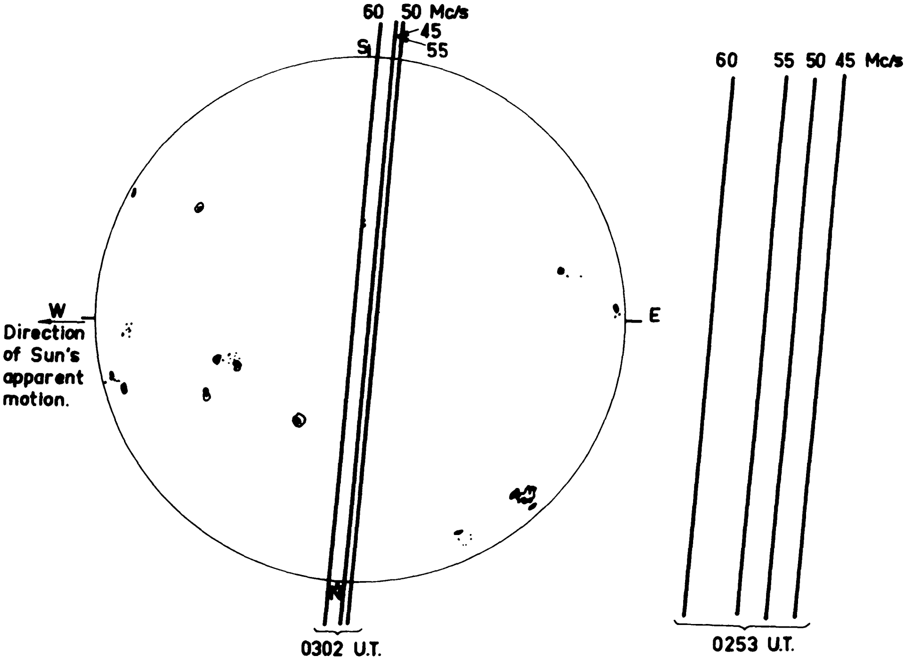

FIG. 1. Showing the lines on which the centroids of the sources of two groups of type III bursts were located at five different frequencies. The two events occurred on the same day (1958 June 5).

another. In the one near the center, all frequencies originate from near the same N-S line; in the other, which is beyond the limb, the characteristic wide dispersion in directions of arrival is evident. Fig. 2 shows the positions (E or W angular displacement from the center) of eleven type III groups plotted as a function of frequency. In two cases the positions of the Hα flare were available, and these are seen to lie near the corresponding sources of the highest radio frequency recorded.

* One interesting exception was the observation of a U-burst, of the kind described by Maxwell, Swarup, and Thompson [4], in which the position of the "forward" and "return" branches differed appreciably from one another.

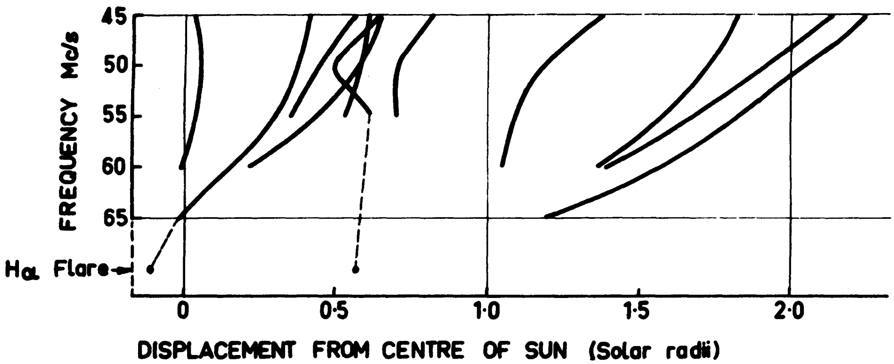

FIG. 2. The variation with frequency of the positions of eleven sources of type III bursts or groups. The positional coordinate represents the displacement (approximately east or west of the center of the sun's disk) of the centroid of the source. The events were recorded on different days between 1958 June 4 and July 7.

These observations indicate that the lower frequencies originate not only at later times but also at greater heights than the higher frequencies. They therefore strongly support the hypothesis of an outward-traveling exciting agency. Quantitatively, the transverse velocities are found to exceed 10^5km/second in some cases of limb events; while this is of comparable magnitude to the radially-outward velocities deduced from spectra, there are individual cases where the transverse velocity is greater by a factor of between 2 and 5. This may mean that we are dealing with speeds much closer to the velocity of light than was previously suspected. The reason for the discrepancy is that sources beyond the limb often originate from heights considerably greater than those given by the standard spherically symmetrical models of the corona. This is consistent with other optical and radio evidence, which indicates that the electron density above active centers is much larger than that given by the standard models.

In this discussion we have neglected the possible effects of refraction in the solar atmosphere. In the case of a spherically symmetrical corona, at least, these would tend to increase the value of transverse velocity.

2. TYPE II BURSTS

At meter wavelengths, the dominating component of great outbursts of radio emission at the time of certain large solar flares is the type II event [5]. In their essential structure, type II bursts seem to be similar to type III bursts except that the time scale is increased by a factor of one or two hundred. The radiation of these slow-drift bursts is believed to originate in a similar manner to that discussed above for type III bursts, but now the velocity of the outward-moving disturbance is much slower — some 500 km/second. We might, therefore, expect type II bursts to exhibit the same general pattern in their positional characteristics; i. e., that the position should be independent of time but should show angular dispersion with frequency.

Two type II bursts have been recorded with the new interferometer, and both cases support this prediction. Apart from some scattered deviations, which could be due to scintillation, the positions at any one frequency remain approximately constant, and the mean positions at different frequencies show the usual systematic displacements from the optical flare. The two cases are illustrated in Figs. 3 and 4, which will be discussed in more detail below. In one case (Fig. 3) the flare is located near the central meridian and the type II agency appears to move away from the flare with an eastward component of transverse velocity of about 250 km/second; in the second (Fig. 4) the flare is located near the east limb and the apparent eastward transverse velocity is of the order of 2000 km/second. Again we find velocities substantially greater than those calculated from the spectrum. If this increase is real, the velocities of type II disturbances would correspond more closely [6] to those of the corpuscular streams, which have been postulated

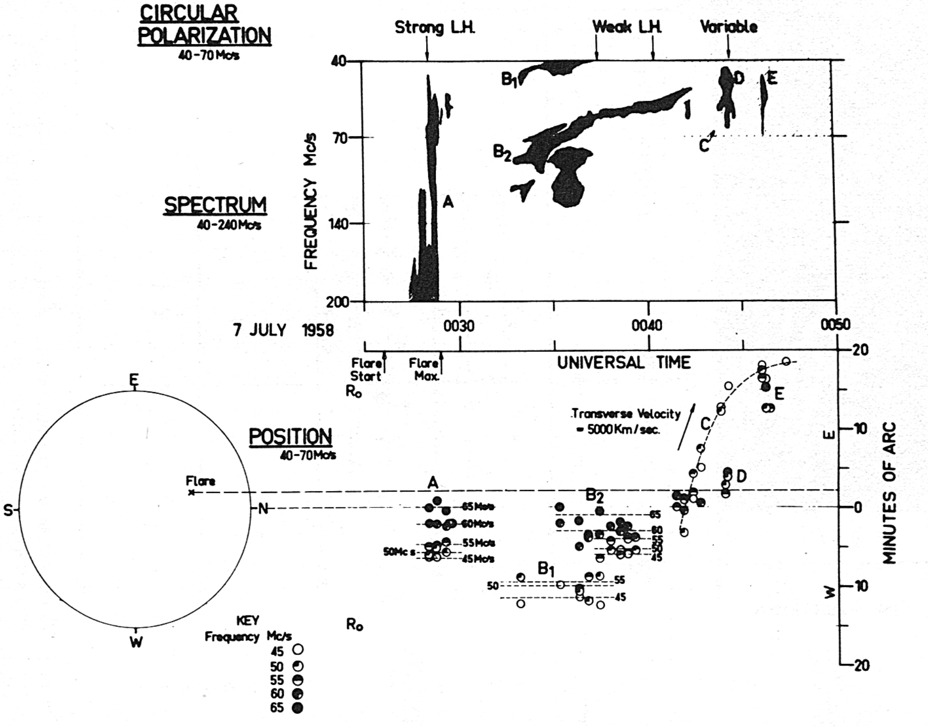

FIG. 3. The polarization, spectrum, and position data recorded during an outburst at the time of a flare of importance 2. Dark areas in the spectral diagram correspond to regions of high intensity in the time-frequency plane. The feature A is a group of type III bursts and associated continuum, B_1 and B_2 are two bands (not obviously harmonically related) of the type II burst, C (the background continuum) is the type IV burst, and D and E are transient features superimposed on the type IV continuum. [NOTE: A second flare of importance 3+, located about 3.5 minutes of arc W of that plotted, commenced at about 01^h40^m U.T. and continued until after 02^h. This is believed to be associated with a later radio outburst, starting at 01^h, and not with the one plotted.]

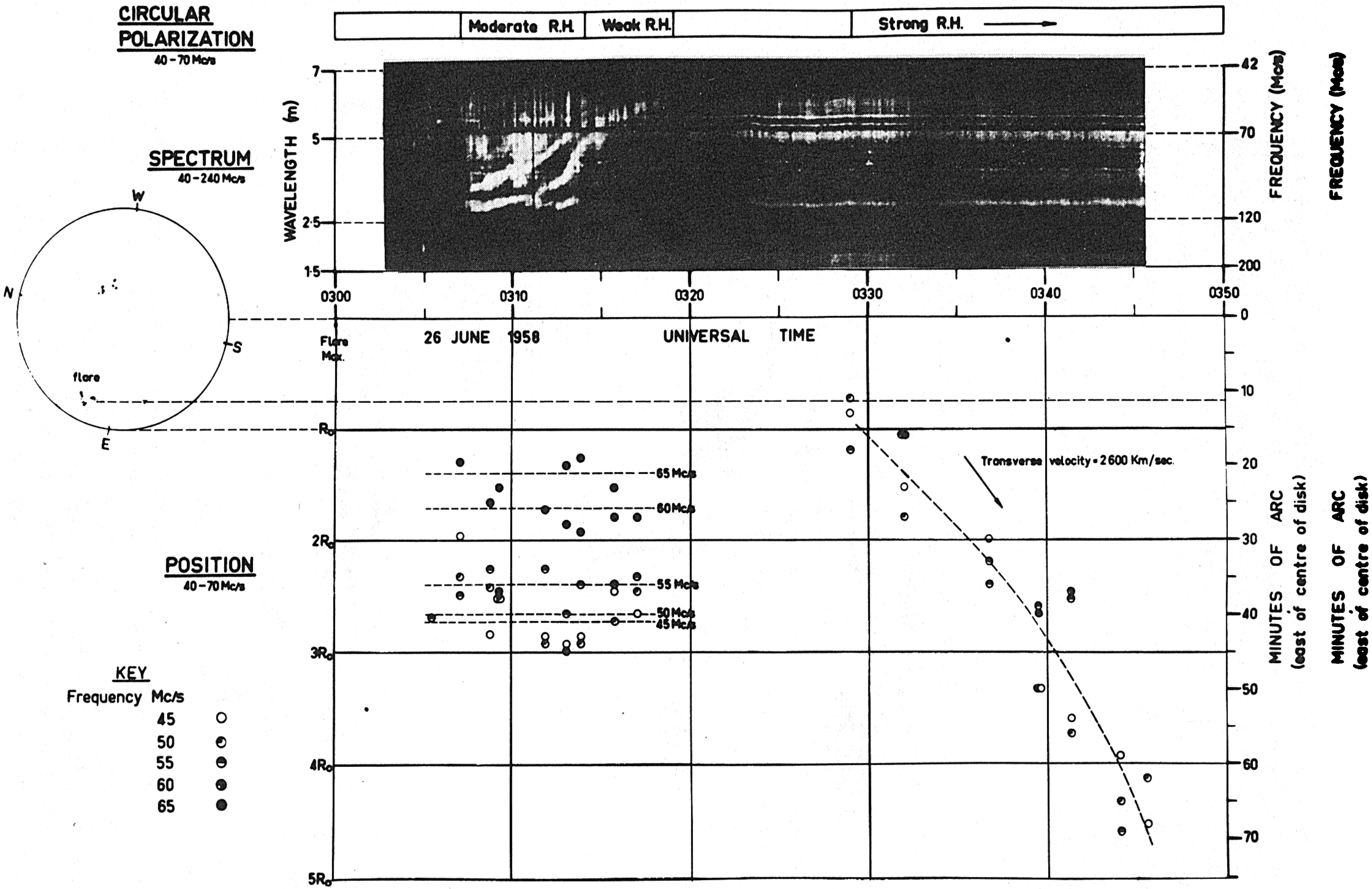

FIG. 4. The polarization, spectrum, and position data recorded during an outburst at the time of a flare of importance 2. The earlier section of the outburst is a type II burst, the later a type IV. [NOTE: In this case errors in position of as much as ±4 minutes of arc may be present since only the short-base (¼ km) interferometer was used.]

to account for the terrestrial magnetic storms and aurorae which follow 1 to 3 days after certain flares.

3. TYPE IV BURSTS

Boischot [7] has established that at 169 Mc/s the type II burst is often followed by a weak, smooth enhancement lasting some tens of minutes during which the source at a given frequency may move across the disk, usually outward, with a velocity of the order of 500 km/second. This he calls the type IV burst. It now seems probable that at least some of the earlier observations of transverse motions, which were made by Payne-Scott and Little [8] at 97 Mc/s, referred to this class of event. Haddock [9] and Maxwell *et al.* [4] have also reported phenomena that they believe to be type IV bursts in the frequency range 100 to 600 Mc/s.

During the two large outbursts previously mentioned, the type IV event was detected in the frequency range 40 to 70 Mc/s. In each case the intensity was estimated to be $\sim 10^{-20}$ watts $m^{-2}(c/s)^{-1}$; while the continuum was inconspicuous on the ordinary spectrographic records, it appeared clearly as a fringe pattern on the swept-frequency interferometer records. In both cases the radiation was partially polarized and, during its lifetime, the source moved transversely by at least one solar radius.

Figs. 3 and 4 show our observations of spectrum, polarization, and position for the two events. In the case of Fig. 3, the flare (near the central meridian) accompanies an outburst consisting of 3 distinct phases: the type III group, which occurs near the start of the flare; the type II burst, which follows after 5 minutes and lasts for 6 minutes; and the type IV burst, which lasts an additional 10 minutes. In the type IV burst, no systematic dispersion is evident, all frequencies arriving from about the same source region. From the observed angular velocity of the source, we deduce a westward component in the transverse velocity of about 5000 km/second.

In the second case (Fig. 4), the flare (near the east limb) accompanies an outburst containing bursts of types II and IV only. The positional data conform to a general pattern similar to the first case, but here, during the type IV phase, we witness the remarkable phenomenon of a source that moves transversely from near the flare position to a position nearly 4 solar radii beyond the limb.

These observations of type IV bursts are generally consistent with Boischot's results, obtained with the Nançay interferometer, although in our two cases the velocities were rather higher than those he reported as typical. Our observations show further that in the type IV burst, unlike types II and III, the instantaneous position of the centroid of the source is largely independent of frequency. This strongly supports the conclusion that the type IV bursts are not caused by plasma oscillations.

4. A FURTHER TYPE OF RADIO BURST

In the course of this investigation we have recorded positions of a number of the broad-band enhancements that are often observed at the time of, or shortly after, the occurrence of type III bursts (see, for instance, [2], Plate 4). Such enhancements last for $\frac{1}{2}$ to 3 minutes, and can reach very high intensities ($\sim 10^{-18}$ watts $m^{-2}(c/s)^{-1}$) over a bandwidth of some tens of megacycles per second with the peak frequency usually below 100 Mc/s. The complete frequency range of the enhancements is not known, but according to a recent analysis by Neylan (personal communication) the probability that a group of type III bursts is accompanied by a simultaneous disturbance at *centimeter* wavelengths is greatly increased if the type III group is associated with one of these enhancements. This suggests the possibility of extremely broad-band emission.

On several occasions the source of this radiation has been observed to exhibit substantial outward transverse movements, at any one frequency, with velocities of the order of 3000 km/second. Thus, while the duration, intensity, and frequency range of these enhancements differ markedly from those of the type IV bursts, their transverse motion appears to be similar. It is possible that they are initiated high in the corona by the type III disturbance, while the type IV bursts may be initiated by the associated type II disturbance.

In this phenomenon we are dealing with yet another distinctive type of radio event. For the purposes of subsequent reference and of stimulating the international reporting of this class of event we suggest a further extension of the numerical classification by calling it type V.

5. CONCLUSIONS

The new results given in this paper are summarized below:

1. The position on the sun's disk of the source of single-frequency radiation in a type III burst does not change during the lifetime of the burst. However, different frequencies originate in different positions, and this effect is most marked for events beyond the limb. From the differences in the times of arrival and the positions of different frequencies, we deduce that a burst is excited by an agency that travels with an apparent transverse velocity sometimes exceeding 10^5 km/second. This strongly supports the previous interpretation of spectral data, but suggests speeds much closer to the velocity of light.

2. From the limited evidence provided by two cases, we conclude that the position on the sun's disk of the sources of type II bursts varies, as in the type III bursts, with frequency but not (systematically) with time. Again, the speed of the exciting agency is probably greater than that previously inferred from spectral data (~ 500 km/second).

3. The position of the centroid of the moving sources of type IV bursts is found to be essentially independent of frequency. This confirms the conclusion that the emission process is not associated with plasma oscillations.

4. The intense low-frequency continuum sometimes associated with type III bursts is found to show similar movements as those of the type IV sources.

ACKNOWLEDGMENTS

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Discussion

Haddock: The delay of type IV after type II is less at higher frequencies than at lower, in the few cases so far recorded. Now similarly, perhaps, the proposed type V follows type III in our higher frequencies (100 to 600 Mc/s) immediately, whereas at your frequencies (40 to 70 Mc/s) you find a type V delayed about one minute after type III. I suggest, therefore, that types V and IV are possibly caused by the same process.

Denisse: It is remarkable that the positions of the fundamental B_1 and the harmonic B_2 of type II do not correspond to the same position. Is it a question of an effect of refraction which acts only on the fundamental, or have you another explanation? You observe type V only on long wavelengths. To what extent is this limitation due to the sensitivity of your receiver?

Roberts: I do not understand this result either. I saw the paper for the first time yesterday and have not had the opportunity to discuss it with Wild. I think type V bursts do have a spectrum in which, in the meter-wave region, the intensity increases toward the longer wavelengths. However, the result found by Neylan, that type V bursts seem to be accompanied by bursts at centimeter wavelengths, suggests an extension to very high frequencies. Type V bursts are often very intense at meter wavelengths (about 10^{-18} watts $m^{-2}(c/s)^{-1}$ at 50 Mc/s).

Wild (submitted 1958 October 22): As presented in Fig. 3, the dynamic spectrum certainly looks like a harmonic relation between bands B_1 and B_2. However, this sketch, which is reproduced from the original record after a

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contraction of the time scale by a large factor, does not show the detailed structure. Examination of the original record shows a complete absence of detailed correspondence between the two bands, so there is no evidence for a harmonic relationship. Rather, I suggest that the two bands represent two separate ejections from the same flare, a phenomenon commonly inferred from type II spectra. A remark to this effect has been added to the legend of Fig. 3.

Minnaert: Apparently, when different type III bursts are compared, the emission of a given frequency does not always appear at the same height. It may be asked whether this shows that the structure of the corona above the flare varies considerably. Assuming that we know the location of the flare and assuming that the motion is radial, it should be possible to correct for the projection effect and to test whether there are deviations in the coronal structure. It would be remarkable if there were great deviations, since these would have to be already in existence before the occurrence of the flare.

Roberts: At present there are not sufficient observations to decide whether the emission at a given frequency always occurs at the same height in the corona. This will evidently have to be tested on a statistical basis to remove the effects of projection and nonradial motion.

Pawsey: Wild hopes to use direction and frequency of bursts to determine electron density, but the first step is to collect an adequate sample of observations to determine if the bursts show consistent features from which it may be possible to infer the direction of travel of the disturbance causing a particular burst.

Cohen: Type III bursts sometimes are weakly polarized at 200 Mc/s, suggesting that the source is somewhat above the level $y = 1 - x$, so that the extraordinary mode can have somewhat greater absorption than the ordinary mode. A magnetic field of about 15 gauss is sufficient to explain the discrepancies between electron densities discussed above.

Mathewson: The increase in electron density above active regions on the sun inferred from movements of type III bursts agrees with the conclusion from the slowly varying decimeter component that high densities always occur above these regions.

Hartz: The results assume that the radiation originates at the plasma level, but you have not said how this radiation could escape for limb events in which the plasma level and the escape level do not coincide but are *very* far apart.

Wild (submitted 1958 October 22): There is now ample evidence that the fundamentals of type II bursts escape from much greater distances from the center than would be permitted by theory that assumes a smooth spherically symmetrical corona (see paper 35 by Roberts). But, if the theory is modified to take account of scattering in coronal irregularities, escape from the plasma level near the limb becomes possible. The question, however, does not necessarily arise in the limb event presented here (Fig. 4), since the received radiation could well be a harmonic of the plasma frequency.

Hey: How do velocities deduced from the radio observations compare with the velocities of corpuscular streams deduced by geophysical effects? This might have an important bearing on the origin of the radio emission; for instance if, as Westfold suggested, the radio burst is related to a shock wave moving out in the solar atmosphere. One would then expect the velocity of the shock front to be greater than that of the corpuscular flow; also the shock would result in an increase in electron density, which is necessary to explain the height of the region of emissions in the solar atmosphere.

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